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Techniques for producing well characterized scattering media from dielectric liquid emulsions and results of measurements of optical pulse stretching and attenuation due to scattering in these systems are outlined.		

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WAVE PROPAGATION IN PARTICULATE MEDIA

Richard A. Elliott

Annual Summary

April 15, 1980 - April 30, 1981

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## Wave Propagation in Particulate Media

### Introduction

The purpose of this project is to study optical propagation in a medium consisting of random, discrete scattering centers with a view to establishing the effects of clouds and fogs on optical communication systems. The degree of pulse stretching, power loss and beam spreading are to be determined as functions of the scattering geometry and the physical properties of the scatterers and compared with the predictions of theoretical models.

An appropriate scattering medium for these experiments is an emulsion of two dielectric liquids since the indices of refraction of both the scatterers and the bulk medium can be varied by choosing different substances and the size of the droplets of the dispersed phase can be controlled by the method of preparation. In addition, emulsions can be stabilized with surfactants and can have much higher number densities than can be maintained in cloud chambers. This allows one to simulate the effect of say a kilometer of cloud in a laboratory scale scattering experiment.

During the period just ended, techniques for producing and characterizing the scattering emulsions have been developed and refined. Optical pulse propagation studies have also been undertaken. The attenuation and stretching of pulses propagating through the emulsion have been measured at varying path lengths up to an optical thickness of ten. This work is described below.

## Technical Progress

### i) Scattering Medium Preparation

It is important that the droplet size distribution of the emulsion be well characterized and that the refractive indices of both the dispersed and bulk phases be known. The latter are well known for most substances and in any case are easily measured. The size distribution can be determined directly, if tediously, by microscopic examination. It is also possible to use Mie scattering theory to infer both the relative refractive index and the size of the scatterers from the angular scattering functions of the medium if a sufficiently thin layer is used to eliminate multiple scattering effects. To date we have relied on microscopic study of the emulsions in refining our preparation techniques. An apparatus for measuring the angular scattering function has been built and will be used to measure the moments of the scattering function directly.

One emulsion we have been working with is an oil-water system stabilized with sodium dodecyl sulphate (SDS). We have found that mineral oil and 0.2% by weight SDS in water form stable emulsions and the volume fraction of the oil droplets can be made as great as a few percent without problems of agglomeration. The index of refraction of the oil is 1.4802 and that of the bulk phase is 1.3332 yielding a relative index of 1.1103. Other substances can and will be used to obtain higher relative indices, e.g., di-iodomethane in water yields a relative index of 1.304. Up to the present we have used the oil-water system to perfect our method of producing droplet distributions with a narrow size range.

The standard preparation procedure is to vigorously agitate a 1% by volume oil/0.2% SDS/water mixture to form a coarse emulsion which is then passed through an 8  $\mu\text{m}$  Nuclepore filter. This produces an emulsion with droplets ranging in size from approximately 1  $\mu\text{m}$  to 20  $\mu\text{m}$ . Although there are more droplets in the midrange it does not appear possible to adequately control the size by choice of a different filter pore size. Also, the variance in diameters is excessive. Since the rate at which the oil droplets rise due to buoyancy is proportional to the square of their diameter it would seem relatively simple to exploit this to obtain droplets of uniform size. However, as a practical matter, the speeds involved are so low (100  $\mu\text{m}/\text{minute}$  for 5  $\mu\text{m}$  diameter droplets) that great care has to be taken to isolate the system thermally and mechanically to avoid convection currents and mixing in the separation apparatus.

The procedure now in use is to take raw emulsion direct from the filter and with it fill a column 50 cm high with a hydraulically controlled "shutter" located 10 cm from the top. After a time calculated to allow all droplets of a given size to rise 40 cm the shutter is closed, the top portion of the emulsion saved, and the lower portion discarded. This operation is repeated several times with the retained emulsion being progressively enriched with large droplets. The final step involves waiting for a somewhat shorter period of time calculated to rid the emulsion of droplets greater than a desired size. Figure 1 shows the droplet size distribution obtained in this manner (solid lines) and the distribution expected (dotted lines). This particular separation was designed to obtain a distribution centered on 8  $\mu\text{m}$ . The initial stage

of the separation was repeated three times with the waiting period, 26 hours, calculated to be that required for 8  $\mu\text{m}$  droplets to rise 40 cm. The final stage, a 12 hour waiting period, was calculated to remove all droplets 12  $\mu\text{m}$  in diameter or greater. The variance in diameters expected from this procedure is 1.9  $\mu\text{m}$ ; that measured is 2.2  $\mu\text{m}$ .

The major problem with the outlined procedure is the low efficiency and the time required to produce a sufficient volume of the desired emulsion for the optical experiments. In principle the droplet size distribution can be further narrowed by repeating the procedure more times. Since it takes more than twenty-four hours for a single stage of the separation process and good thermal control requires working with relatively small volumes several weeks are needed to make the 15 litres needed for the optical experiments. The speed with which the droplets move is proportional to the difference in density of the two liquids. It is therefore anticipated that more closely monodisperse distributions will be attainable with di-iodomethane since it has a density of 3.3254.

An alternative technique for producing monodisperse emulsions based on the method used in ink-jet printers is also being explored. This involves imposing small high frequency, regular fluctuations in the oil flow rate through an orifice by means of an r-f driven piezoelectric crystal. This causes a periodic ripple on the surface of the jet emerging from the orifice. The action of surface tension then causes the stream to break into uniform droplets. A single orifice system has been constructed and worked reasonably well but the rate of droplet

production is too low to be useful for our purposes. A multiple orifice system which should increase the production rate is now being built.

ii) Optical Measurements

The pulse stretching and attenuation measurements which have been made utilize a cylindrical scattering cell 10 cm long by 40 cm diameter. The cylinder is mounted with its axis horizontal and rotates at 1 rpm in order than an emulsion can be placed in the cell and maintained for long periods of time without problems of agglomeration or creaming, i.e., the formation of a layer of oil droplets on the surface. The incident light enters along the cylinder axis through a 2 cm diameter, anti-reflection coated, window which can be moved over a range of 0.5 to 10 cm from the 40 cm diameter, plate glass, exit window. This allows a full range of measurements to be made for a variety of path lengths and optical densities with each type of emulsion.

The light source for these experiments is a passively mode-locked Nd:YAG laser which we have assembled. Each mode-locked burst from the laser contains around twenty 80  $\mu$ J pulses each 35 psec in duration and spaced at 10 nanosecond intervals. The pulse train then passes through an angle tuned KDP crystal frequency doubler to convert some of the infrared (1064 nm) pulses to the visible (532 nm). The green pulses carry around 20  $\mu$ J energy and are 25 picoseconds in duration. A single one of the green pulses is selected from the train and transmitted through the scattering cell. The radiation emerging from the cell is detected and displayed with a Hamamatsu streak camera capable of 5 picosecond time resolution. A portion of the incident pulse is diverted by a beam splitter to a variable time delay line, around the scattering

cell, and to the streak camera. This allows both the incident pulse and scattered pulse to be displayed on the same streak record.

An event captured by the streak camera is first displayed on a TV monitor. There it is examined to ensure that both the reference and scattered pulses have been recorded and that the incident pulse is a "good" one. (The output of the laser is somewhat variable and occasionally the single pulse selected is low in energy and misformed.) The streak record, which is already in digital format, is then recorded on magnetic tape for subsequent computer analysis. Figure 2 is one such record. In this case the scattered pulse has traversed 10 optical thicknesses of the emulsion and it is obviously broader. Figure 3 is the average of several individual records. The scattered pulses have been shifted to indicate the actual delay experienced relative to that which they would have had if pure water were in the cell rather than emulsion.

An example of the stretching or broadening of the pulses observed as a function of optical thickness is displayed in Figure 4. The degree of stretching,  $\Delta T$ , was taken to be,  $\Delta T = [T_s^2 - T_r^2]^{1/2}$  with  $T_s$  and  $T_r$  being the full width at half maximum of the scattered and reference pulses. The regression line has a slope of 1.05, indicating that the stretching is directly proportional to optical thickness over this range. This disagrees with the  $\tau^{3/2}$  behavior predicted by Monte Carlo simulation\* for this range of optical thicknesses. The attenuation of the scattered pulses as a function of optical thickness in the same

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\*G. Lee, C. Ciany, G. Schroeder and J. Fenier, "Availability Models for Space-to-Earth Optical Communication Links," McDonnell Douglas Astronautics Laboratory Report.

emulsion is shown in Figure 5. The optical thickness was determined by direct measurement of the attenuation in a thin layer at 532 nm and agrees semi-quantitatively with that calculated from the observed number density and size distribution.

#### Summary

A facility designed to study optical pulse propagation in a medium composed of random discrete scatterers has been established. Techniques for producing and characterizing scattering media with a range of desired properties such as index of refraction, number density, and size distribution have been developed and demonstrated.

Pulse propagation studies which demonstrate the capabilities of the experimental setup have been performed. It has been shown (Figure 4) that pulse stretching as short as a few picoseconds can be measured. The absolute precision of the streak camera used as a detector is of the order of 5 psec for a single event. By averaging over several identical events and use of a reference pulse this can be reduced further to the  $\pm 2$  psec range indicated in Figure 4. The 5 psec broadening observed at a path length  $z = 3.3$  cm and optical thickness,  $\tau = 3$ , represents the time resolution limits of our apparatus.

The attenuation measurements displayed in Figure 5 show the exponential decrease of the direct beam out to  $\tau \approx 6$  followed by the expected slower decay at greater thickness due to multiple scatter effects. The sensitivity of the streak camera has not fully been exploited and a Nd:YAG amplifier is also available to increase the incident pulse energy. This will allow measurements on systems having optical thicknesses of the order of 100.

A complete range of pulse stretching, delay and attenuation measurements will be made on several emulsion types over the next few months. Time permitting, depolarization, beam spreading, off axis pulse propagation and the effects of bimodal droplet distributions will be studied.

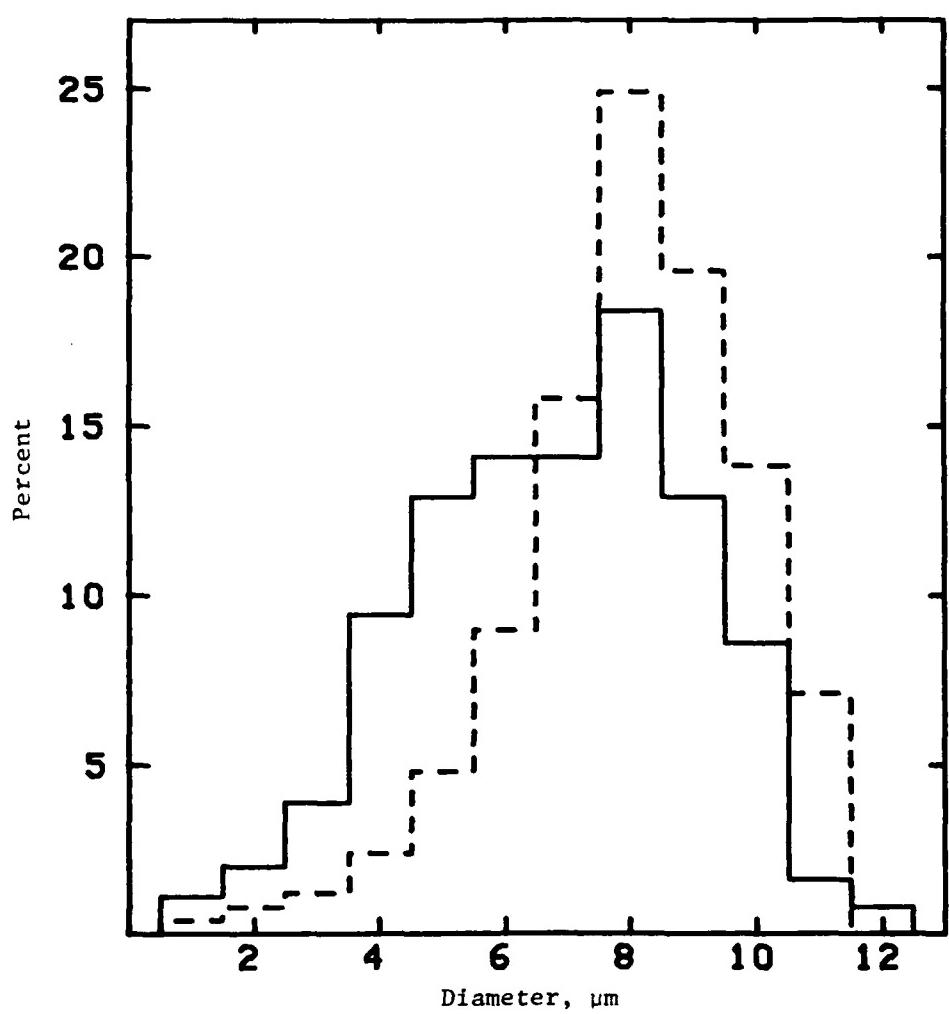


Figure 1. (—), Measured oil droplet size distribution, mean diameter 6.8  $\mu\text{m}$ , standard deviation 2.2  $\mu\text{m}$ .  
(- - -), Expected distribution, mean diameter 7.95  $\mu\text{m}$ , standard deviation 1.9  $\mu\text{m}$ .

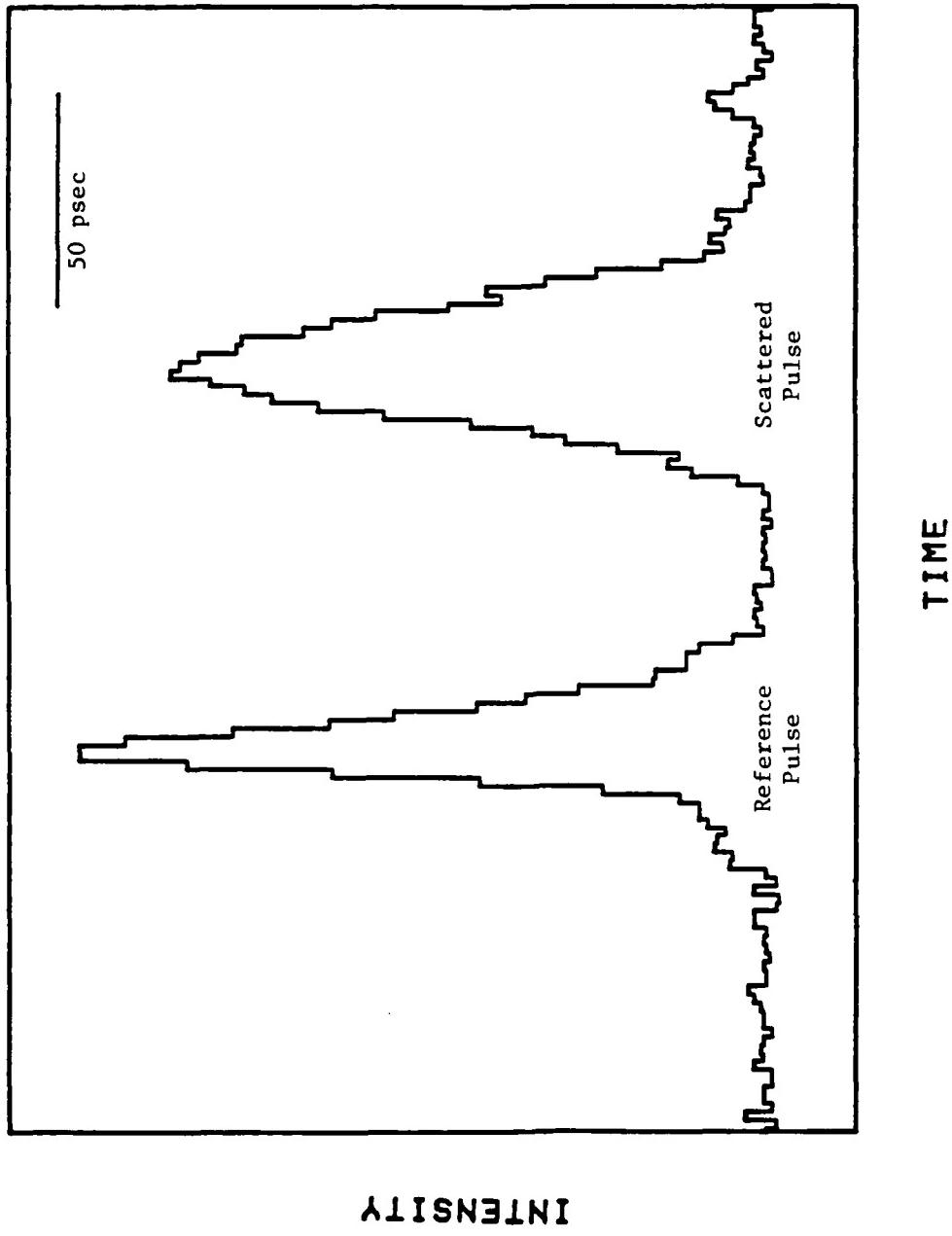


Figure 2. Streak camera readout showing incident (reference) pulse and pulse after propagation through 11.3 cm of emulsion ( $\tau = 10.3$ ).

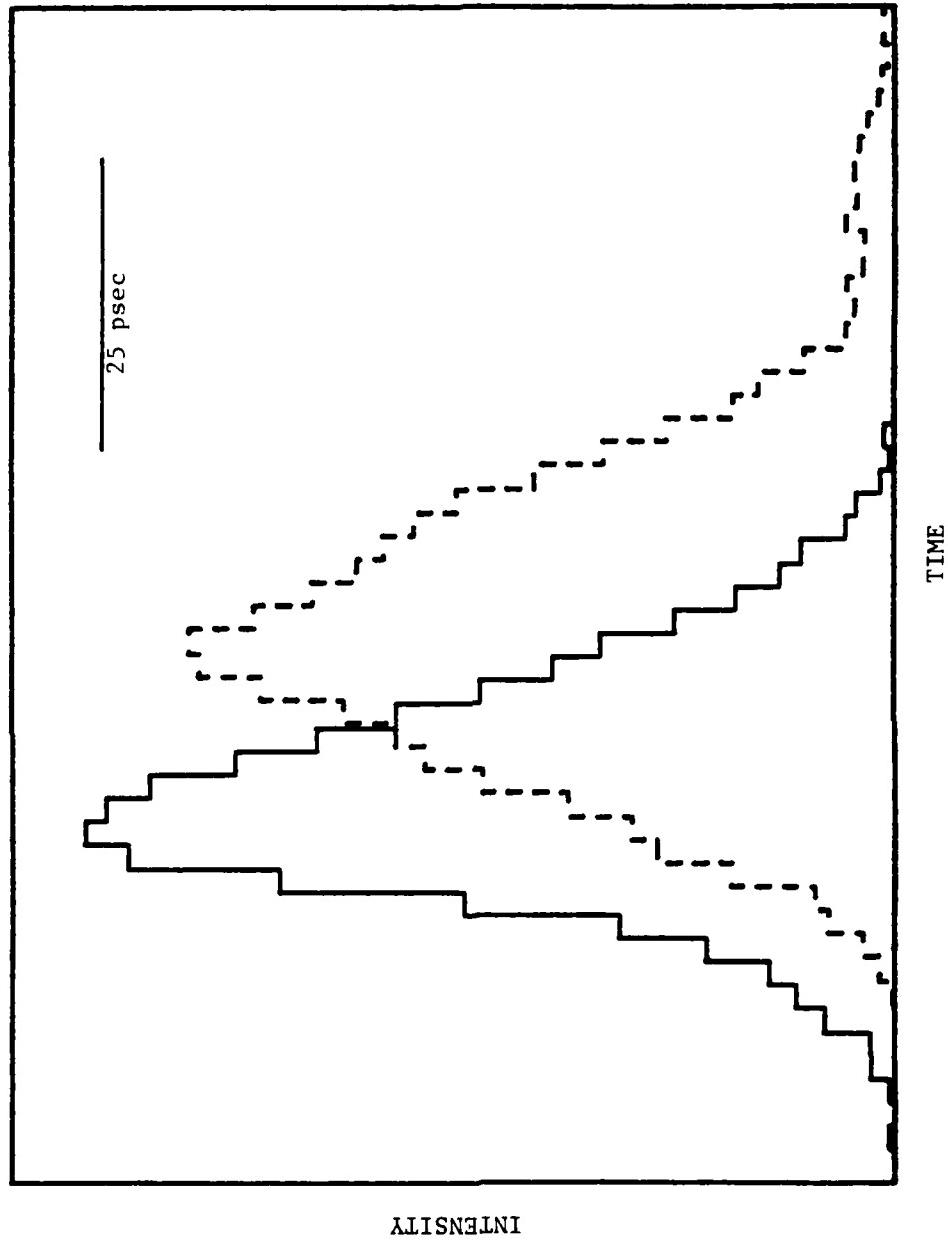


Figure 3. Average of 5 records like that shown in Figure 2. The scattered pulse (----) has been located to show the extra delay experienced due to scattering.

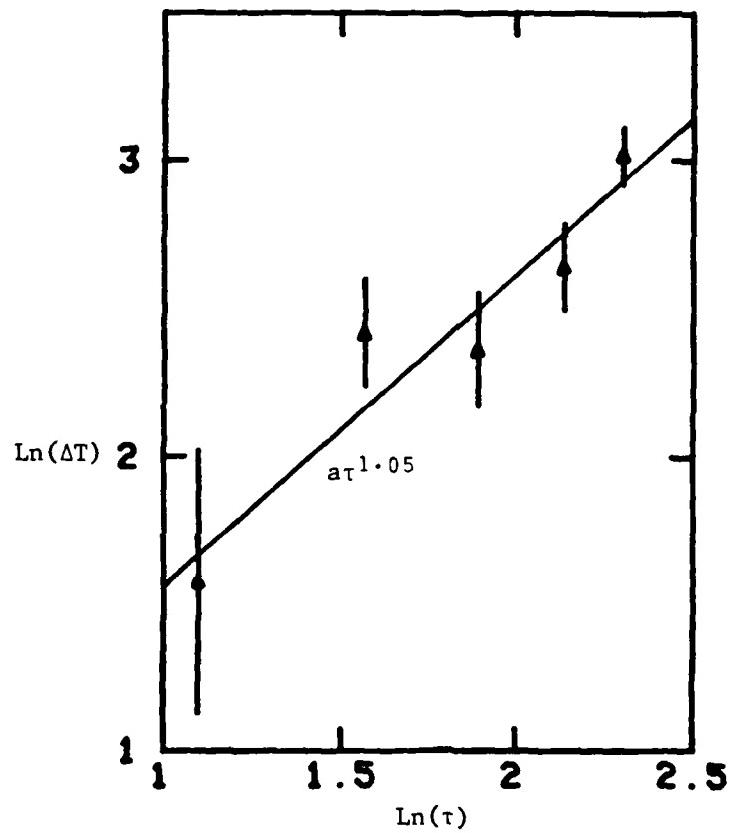


Figure 4. Pulse stretching versus optical thickness.  
The regression line has a slope of 1.05  
indicating a linear relationship over this  
range of optical thickness (3 to 10.3).

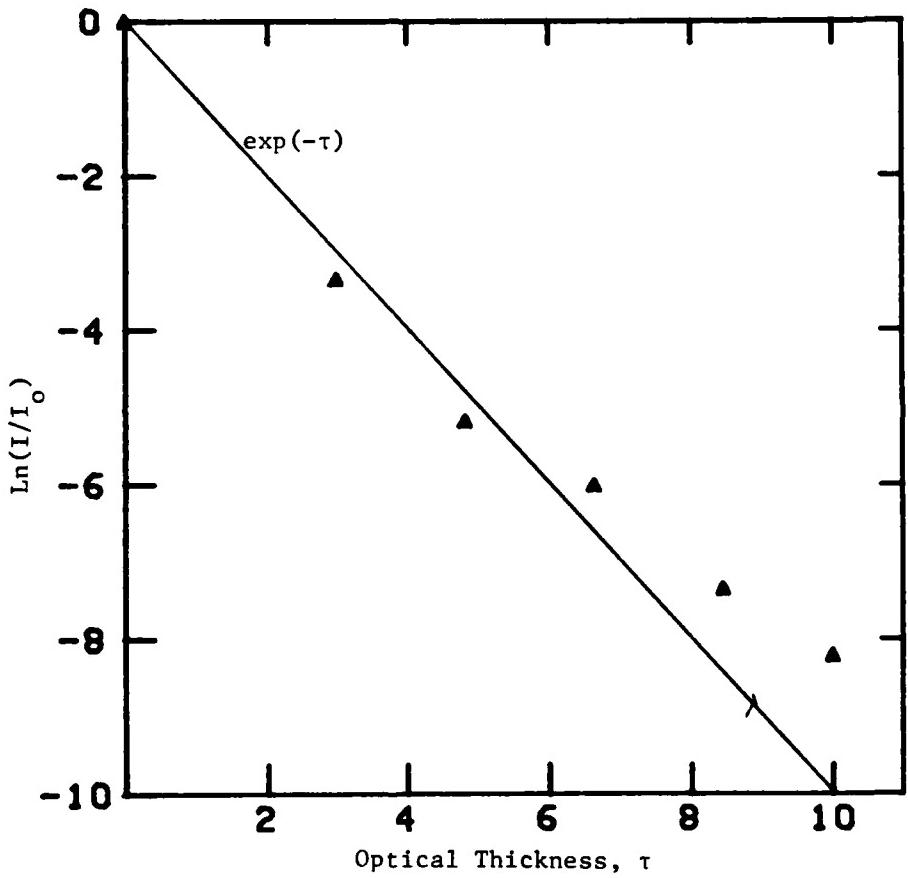


Figure 5. Pulse attenuation versus optical thickness.

